RHIC Beam Energy Scan Program
Experimental Approach to the QCD Phase Diagram

Grazyna Odyniec / LBNL, Berkeley

central Au+Au @ 7.7 GeV event in STAR TPC
Outline:
Main goal of BES: study QCD phase diagram
Heavy Ion Collisions – the only experimental tool
BES @ RHIC: Physics goals and observables:
  - search for the CP and 1st order phase transition
  - demonstrate the onset of deconfinement (QGP)
Run 10 – STAR experience
Run 11
Theory at the “edges” is believed to be well understood:
1. Lattice QCD finds a smooth crossover at large $T$ and $\mu_B \sim 0$
2. Various models find a strong 1st order transition at large $\mu_B$
So, there must be a critical point, but where?

Lattice at $\mu_B \neq 0$: serious problems, several methods on lattice, no agreement so far:

$\longrightarrow$ CP range: $160 < \mu_B < 500$ MeV

Given the significant theoretical difficulties, data may lead the study of QCD phase diagram

$\longrightarrow$ Beam Energy Scan Program at RHIC will cover this range
Beam Energy Scan at RHIC: $\sqrt{s_{NN}} \sim 5$-50 GeV
experimental window to QCD phenomenology
at finite temperature and baryon number density

at RHIC: indications of sQGP but remain unknown:
- boundary between hadronic and partonic phases
- critical point

HOW to investigate it?

BES @ RHIC

160 MeV $< \mu_B < 500$ MeV
also: SPS, FAIR (fixed target)
RHIC and BNL from space

RHIC = Relativistic Heavy Ion Collider
Located at BNL = Brookhaven National Laboratory
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory (BNL), Upton, NY

\[ v = 0.99995 \cdot c = 186,000 \text{ miles/sec} \]

Au + Au at 200 GeV
Relativistic Heavy Ion Collider (RHIC)

- 2 concentric rings of 1740 superconducting magnets
  - 3.8 km circumference
  - counter-rotating beams of ions from $p$ to $Au$
- max center-of-mass energy: $AuAu$ 200 GeV, pp 500 GeV
Search for:

(1) indications of the existence of Critical Point & phase transition
   • fluctuation measures
     • higher moments of net proton distribution (kurtosis)
   • azimuthally-sensitive femtoscopy
   • elliptic & directed flow
   • …

(2) disappearance of signals of partonic degrees of freedom seen at 200 GeV
   • disappearance of constituent-quark-number scaling of $v_2$
   • disappearance of hadron suppression in central collisions
   • disappearance of ridge
   • local parity violation
   • …

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Critical Point search – Fluctuations maximized at CP
example: e-by-e fluctuations in $K/\pi$ ratio

$\sigma_{\text{dyn}}$ (%)

$\sqrt{s_{NN}}$ (GeV)

$\sqrt{s_{NN}}$ (GeV)

$\sigma_{\text{dyn}}$ (%)

PRL 103, 092301 (2009)

NA49 fluct. > STAR fluct. ?
CP at lower energies ? (but diff. acceptance).

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more sensitive: - Higher Moments

**Thermodynamics:** Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point.

**Lattice QCD:** Spikes for both $\chi_B$ and $\chi_S$

- Berdnikov, Rajagopal, PRD61, 105017 (00)
- Stephanov, Rajagopal, Shuryak, PRD 60, 114028 (99)
- Hatta, Stephanov, PRL. 91, 102003 (03)

**Observable:**
- Kurtosis of net-proton & net-C
  - connect to lattice calculations!
  - sensitive to long range fluctuations

**Caveats:**
- dynamical effects in collisions
  - finite time and size
  - critical slowing
High moments are more sensitive to critical point related fluctuation.

The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility for conserved quantum numbers such as Baryon number, charge, strangeness…

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Centrality dependence of net-proton Kurtosis

STAR Preliminary:

200 GeV Au+Au ($\mu_B \leq 25$ MeV)

First Kurtosis measurement for net-protons in high-energy nuclear collisions

Monotonic behavior observed at relatively small $\mu_B$ region → baseline

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Disappearance of partonic degrees of freedom (I)
(Onset of sQGP)

disappearance of $n_q$ scaling, disappearance of hadron suppression at high $pt$, … (a long list)

$n_q$ scaling observed at RHIC:

(1) Mass separation at low $p_T$

(2) Light and heavy quarks have similar magnitude of flow

(3) In intermediate $p_T$: separation between baryon and meson band
Disappearance of partonic degrees of freedom (II)

Scaling flow parameters by quark content $n_q$ (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

flow developed in pre-hadronic stage
DECONFINEMENT at RHIC

With lowering energy, disappearance of $n_q$ scaling would suggest that we exit partonic dof world
Will we be able to see it?

Yes, a few M is enough!
Local Parity Violations in Deconfined Medium

1. Under strong magnetic field, when the system is in the state of deconfinement and chiral symmetry restoration is reached, local fluctuation may lead to parity violation.

2. Experimentally one would observe the separation of the charges in high-energy nuclear collisions.

3. In RHIC Beam Energy Scan program - test the model prediction

- the energy when the charge separation disappear => phase boundary


Parity even observable: \( \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \)

Voloshin, PR C62, 044901(00)
<table>
<thead>
<tr>
<th>Collision Energies (GeV)</th>
<th>5</th>
<th>7.7</th>
<th>11.5</th>
<th>17.3</th>
<th>27</th>
<th>39</th>
</tr>
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<tbody>
<tr>
<td>Observables</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$v_2$ (up to $\sim$1.5 GeV/c)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$v_1$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Azimuthally sensitive HBT</td>
<td>4</td>
<td>4</td>
<td>3.5</td>
<td>3.5</td>
<td>3</td>
<td>3</td>
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<tr>
<td>PID fluctuations (K/$\pi$)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>net-proton kurtosis</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>differential corr &amp; fluct vs. centrality</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$n_q$ scaling $\pi/K/p/\Lambda$ $(m_T- m_0)/n&lt;2$GeV</td>
<td>8.5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>$\phi/\Omega$ up to $p_T/n_q=2$ GeV/c</td>
<td>56</td>
<td>25</td>
<td>18</td>
<td>13</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>$R_{CP}$ up to $p_T \sim 4.5$ GeV/c (at 17.3) 5.5 (at 27) 6 GeV/c (at 39)</td>
<td></td>
<td></td>
<td>15</td>
<td>33</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>untriggered ridge correlations</td>
<td>27</td>
<td>13</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>parity violation</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Recommendations of BNL Nuclear and Particle Physics Program Advisory Committee (PAC):

Run 10 (2010):
1. 10 weeks of Au+Au at 200 GeV
2. 12 weeks for a beam energy scan (BES) with Au+Au collisions:
   1. 4 weeks 62 GeV
   2. 8 weeks lower energies
      1. 0.5 week 39 and 27 GeV
      2. 1 week at 18 GeV (10 M)
      3. 2 weeks at 11 GeV (6 M)
      4. 4 weeks at 7.7 GeV (3.6 M)

Sufficient rates for the initial physics program at all energies

“binary” experiment: YES/NO (no “maybe’s” & more statistics needed)
STAR experience with low energy running

9.2 GeV Au+Au
March 2008

for comparison 200 GeV Au+Au
STAR experiment demonstrated capabilities

9.2 GeV results consistent with the published data

only a few $10^3$ events taken during machine test

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Elliptic Flow

STAR and NA49 results are consistent
STAR 9.2GeV $v_2$ fits with the observed trends

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AGS : PLB 474 (2000) 27
PHENIX : PRL 98 (2007) 162301
Pion Interferometry

\[ \pi^- \]

error bars for Au+Au 9.2 GeV are statistical systematic errors < 10 % for all radii


STAR was ready for run 10 ! to take up Beam Energy Scan Program
No SVT (low material)
100% TOF
FTPCs
Large beam pipe
Run 10 – part I of BES@RHIC

Hardware and operation improvements

Main directions of Beam Energy Scan program at RHIC established:
• search for turn-off of sQGP signatures
• search for the evidence of CP and/or 1\textsuperscript{st} order phase transition
• + many other measurements

Strategy: scan available phase space with (6) equally spaced points between 5 and 39 GeV (we already have 62, 130, 200 data), and return to “interesting” regions for more detailed studies in the next year
Train left the station on April 8th with 39 GeV Au+Au collisions …

Run 10:
39, 7.7 and 11.5 GeV Au+Au
to be continued (run 11) next year
Central Au+Au @ 7.7 GeV Event
Typical Au+Beam-pipe @ 3.85 GeV event

Event outside active TPC volume
Au+Au @ 7.7 AGeV - vertex reconstruction – bck!

- Au+beam-pipe events from the beam halo
Au+Au @ 7.7 AGeV – sources of background

Two flanges at ± 4.4 m outside the TPC produced most of the background at the first days.

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vertex distributions though the run …

middle: Day 130

end: Day 147

Superb improvement!

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High Level Trigger (HLT): Vertex

HLT is able to reconstruct online the primary vertices
HLT good event rate is very close to offline QA rate
Priceless redundancy !

Day 146
Online HLT good event rate

~ 9 Hz!
STAR data summary AuAu @ 7.7 GeV

Collected 5.014 M events
- met the goal!
Operated in 10 minutes stores environment
Average uptime ~ 11 hours
Collecting up to 350 k events per day

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Great performance improvement from the CA-D side during the run
## Statistics from Run 10

<table>
<thead>
<tr>
<th>Beam Energy ($\sqrt{s}_{NN}$, GeV)</th>
<th>Minbias (Million)</th>
<th>Central (Million)</th>
<th>High-Tower Sampled Luminosity</th>
<th>FTPC+PMD (Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>355</td>
<td>265</td>
<td>2.6 (nb$^{-1}$)</td>
<td>5</td>
</tr>
<tr>
<td>62.4</td>
<td>140</td>
<td>33</td>
<td>175 (µb$^{-1}$)</td>
<td>3.5</td>
</tr>
<tr>
<td>39</td>
<td>250</td>
<td></td>
<td>62 (µb$^{-1}$)</td>
<td>23</td>
</tr>
<tr>
<td>7.7</td>
<td>5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>11.5</td>
<td>$\geq$ 7.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Commissioning</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Identified Particle Acceptance at STAR

Au+Au at 7.7 GeV

Au+Au at 39 GeV

Au+Au at 200 GeV
Multiplicity at 7.7, 39, and … GeV

Au + Au at Run10, |v_z| < 50 cm

(1/N_{evts}) dN/(dN/d\eta)

Uncorrected dN/d\eta |\eta|<0.5

Data
- 7.7 GeV
- 39 GeV
- 62.4 GeV
- 200 GeV

MC
- 7.7 GeV
- 39 GeV

STAR preliminary
STAR Performance in Run 10
Particle Identification at 7.7 GeV

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Particle Identification – part II

$\sqrt{s_{NN}} = 39$ GeV Au + Au Collisions

Invariant Mass (GeV)
Event Plane Resolutions

Event plan measurements at STAR:

1. TPC \(|\eta| \leq 1\)
2. FTPC \(2.5 \leq |\eta| \leq 4.2\)
3. BBC \(3.8 \leq |\eta| \leq 5.2\)
Summary

• RHIC Beam Energy Scan - Fantastic success!
  Au + Au at 39, 7.7 and 11.5 GeV runs:
  – Met all goals and far exceeded for some data points
    • 7.7 GeV (34 days) and 11.5 GeV (8+3 days): \( N_{\text{events}} > 5 \text{ M} \)
    • 39 GeV (15 days): \( N_{\text{events}} \sim 170 \text{ M events} \)
  – Dramatic improvement of the collider performance at 7.7 GeV
• Preliminary results based on fast offline run 10 data look very promising
• Final calibration results soon

• Last call for predictions on critical point !!!

• PAC in two weeks ... discussion of run 11 begins!
## STAR BES for Runs 11 and 12

<table>
<thead>
<tr>
<th>Run</th>
<th>Beam Energy</th>
<th>Time</th>
<th>System</th>
<th>Goal</th>
<th>New Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>$\sqrt{s_{NN}} = 18, 27$ GeV</td>
<td>2 weeks</td>
<td>Au + Au</td>
<td>100, 150M minbias</td>
<td>HLT</td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s_{NN}} = 200$ GeV</td>
<td>4 weeks</td>
<td>U + U</td>
<td>200M minbias 200M central</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s} = 500$ GeV</td>
<td>5 weeks 6 weeks</td>
<td>$p \uparrow p \uparrow$</td>
<td>trans. $P^2L = 4$ pb$^{-1}$ long. $P^2L = 20$ pb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>$p \uparrow p \uparrow$</td>
<td>pp2pp at high $\beta^*$</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>$\sqrt{s} = 500$ GeV</td>
<td>10 weeks</td>
<td>$p \rightarrow p \rightarrow$</td>
<td>long. $P^2L = 50$ pb$^{-1}$ $P^4L = 15$ pb$^{-1}$</td>
<td>FGT</td>
</tr>
<tr>
<td></td>
<td>or</td>
<td>10 weeks</td>
<td>or</td>
<td>or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s} = 200$ GeV</td>
<td>10 weeks</td>
<td>$p \uparrow p \uparrow$</td>
<td>trans. $P^2L = 8.5$ pb$^{-1}$ long. $P^4L = 4.3$ pb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s_{NN}} = 200$ GeV</td>
<td>10 weeks</td>
<td>U + U or Au+Au</td>
<td>3.5 nb$^{-1}$ U+U or 5 nb$^{-1}$ Au+Au</td>
<td>MTD</td>
</tr>
</tbody>
</table>
Thank you!